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Harmonic frequency characterisations of a CMOS micro fluxgate sensor for low magnetic field detection

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Abstract

A CMOS micro fluxgate sensor, including device design, manufacturing process and harmonic frequency characterizations, is described in this paper. The single-axis device is designed in a planar coil structure with a ferromagnetic core featuring low saturation magnetic induction of 10 µT. The chip is measured 2.08 mm × 1.29 mm and fabricated by TSMC CMOS 0.35 µm 2P4M process. The miniature magnetic core is formed by wet etching process and precisely allocated to the designated position of the sensor chip by using an aligner. To characterize the micro-fluxgate sensor, the output voltage of the induction coil and external magnetic field is especially measured at the excitation, second, third and forth harmonic frequencies respectively. Experimental results reveal that the B-V diagram at excitation and the 3rd harmonic frequencies are well described by even-function behavior while the characteristics at the 2nd and 4th harmonic frequencies are expressed by odd-function operation. Besides, it is also observed that the maximum output voltage amplitudes at odd-order harmonic frequencies tend to occur when the maximum field-to-voltage transfer coefficients (i.e., *dV/dB)* become prominent at even-order harmonic frequencies, and vice versa. To measure the low magnetic field, it is found that the micro fluxgate demonstrates a nearly linear B-V relationship around the zero-magnetism region while the 4th order harmonic frequency is employed. The maximum responsivity can be further enhanced up to 174.62 mV/T. The frequency response of the device is measured as 90 Hz, i.e., a rapid response time of 0.01 s.

Keywords –micro fluxgate; magnetic sensor; harmonic frequency characterisation

1. Introduction

Fluxgate magnetometers are a class of magnetic sensors for measuring low magnetic fields, and they are considered the most sensitive magnetic sensors operated at room temperature. Fluxgate sensors benefit from tiny zero point drift and significant linearity, and enable measurement of DC magnetic fields down to 0.1nT in the recent decades [1-2]. Traditional and early fluxgate sensors included different geometries such as single rod, dual-rod and ring types of coils and had complicated windings [3]. Unfortunately the main disadvantage is its remarkable volume. To meet the emerging applications for miniature components and systems, micro-fluxgate magnetic sensors have been developed and fabricated via CMOS and MEMS technologies [4-5]. In addition to their miniature structure, micro-fluxgate magnetic sensors not only feature planar design, but also consume lower power than traditional ones. Also of recent applications using fluxgate sensors are electronic compasses and non-destructive current inspectors. Besides, fluxgate sensors have played an influential part in modern aviation safety and space exploration [6].

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2. Sensor design and fabrication

In our experiments the planar micro-fluxgate magnetic sensor is composed of an excitation coil, induction coils and a ferromagnetic core, as shown in Figure 1. The excitation coil was 1.195 mm × 1.247 mm and had a line width of 25 µm with a spacing of 1 µm, winded with 23 turns; the individual induction coil was 0.611 mm × 0.623 mm and had a line width of 5 µm with a spacing of 1 µm, winded with 50 turns. The induction coils were overlapped underneath the excitation coil where the magnetic core was deposited upon. All of the coils except the core were implemented by TSMC CMOS 0.35 µm 2P4M process from National Chip Implementation Center (CIC). The core was deposited onto the sensor in the post-CMOS step using a wet-etch technique. The device layout of the planar fluxgate sensor and the micrograph of the fabricated chip which was 2.08 mm × 1.29 mm were depicted in Figure 1 and Figure 2, respectively.

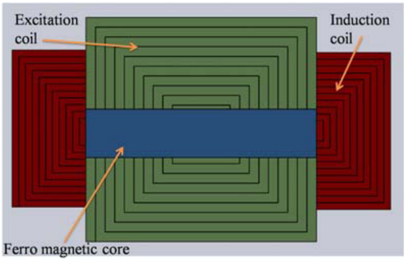

Figure 1: The schematic layout of a planar micro fluxgate.

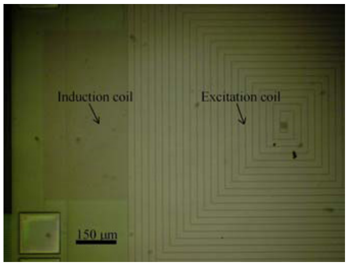

Figure 2: A CMOS micro fluxgate chip (shown in part).

The ferromagnetic metal sheet was attached to a glass substrate using a thin layer of photoresist. With standard lithography the tiny rod of the core metal was formed after a wet-etch step. By employing a precise aligner and the electrostatic force, the tiny core metal was 0.4 mm × 1.235 mm was horizontally adhered to the center of the excitation coil. The magnetic core is a magnetic metal sheet provided by 2714A Metglas™ Ltd., and the saturated magnetic field for it is not more than 10 µT [7], which was perfectly matched with the low magnetic field excited from the planar excitation coil.

3. Experimental method and results

To characterize the micro-fluxgate sensor, an excitation frequency of 25 KHz and an excitation voltage of 5 V were applied, and a lock-in amplifier (SR830, Stanford Research Systems) was employed to measure the output voltage of the induction coil and external magnetic fields were generated by a solenoid that is able to enclose the fluxgate sensor. The output voltage of induction coil were especially measured at excitation (25 kHz), the second (50 kHz), the third (75 kHz) and the forth (100 kHz) harmonic frequencies, as demonstrated in Figure 3 through Figure 6, respectively.

Our experimental results interestingly reveal that the B-V diagram at excitation and the 3rd harmonic frequencies are well described by even-function behaviour while the characteristics at the 2nd and 4th harmonic frequencies are expressed by odd-function operation. Besides, it is also observed that the maximum output voltage amplitudes at odd-order harmonic frequencies tend to occur (near B = 1.4 mT) when the maximum field-to-voltage transfer coefficients (i.e., dV/dB) become available at even-order harmonic frequencies, and vice versa (near B = 1.8 mT). Finally, the micro-fluxgate demonstrates a nearly linear B-V relationship around the zero point region if the 4th harmonic frequency is employed, which is superior to other harmonic extractions and feasible for weak magnetic field measurement. A field-to-voltage transfer coefficient is defined as responsivity to the magnetic field in each harmonic frequency. It was shown that a nearly linear in-phase output voltage around the zero point was found if the 4^{th} harmonic frequency is employed. The quadrature output voltage of the 2^{nd} harmonic frequency was not as linear as that of the 4^{th} harmonic frequency. However, from measurements, we observed that the maximum responsivity corresponding to in-phase 2^{nd} harmonic frequency are 191.79 mV/T and 115.25 mV/T corresponding to in-phase 4^{th} harmonic frequency, respectively. The linear range was estimated from -0.5 mT to 0.5 mT.

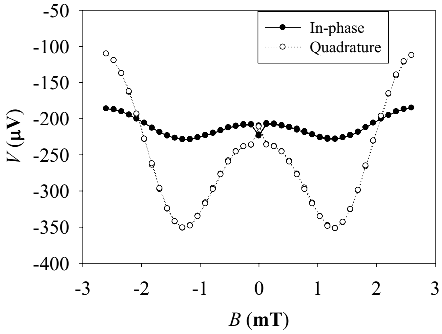

Figure 3: The fundamental frequency.

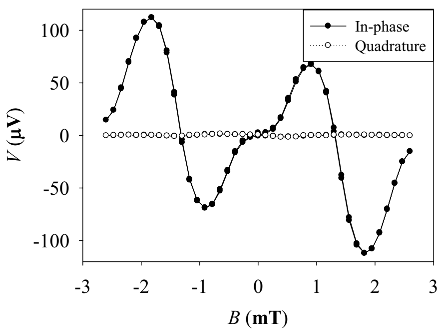

Figure 4: The 2nd harmonic frequency.

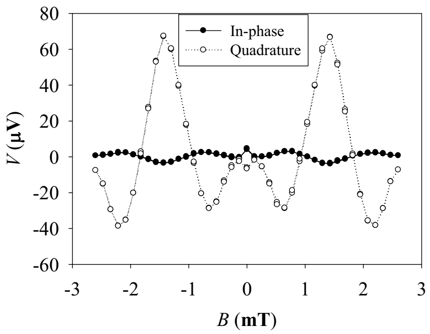

Figure 5: The 3rd harmonic frequency.

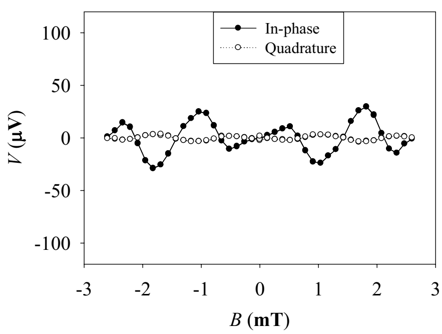

Figure 6: The 4th harmonic frequency.

To improve the responsivity of the 4th harmonic frequency, we regulated the phase between in-phase and quadrature frequencies when measuring the linear range around the zero-magnetism region, so as to stabilise the quadrature output and enhance the amplitude of the in-phase voltage, as shown in Figure 7. As can be seen, the B-V diagram is an odd-function behaviour and symmetrical to the origin. It was found the maximum responsivity of the 4th harmonic frequency can be further improved up to 174.62 mV/T, which is much closer to that of in-phase 2nd harmonic frequency (191.79 mV/T). In addition, the output response to frequency was also investigated and shown in Figure 8, where the frequency response was identified as 90 Hz and a rapid response time equivalent to 0.01 s.

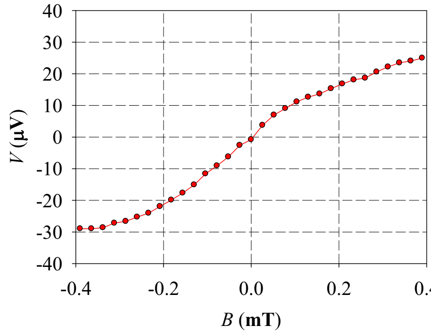

Figure 7: The B-V diagram for improved responsivity of the 4th harmonic frequency.

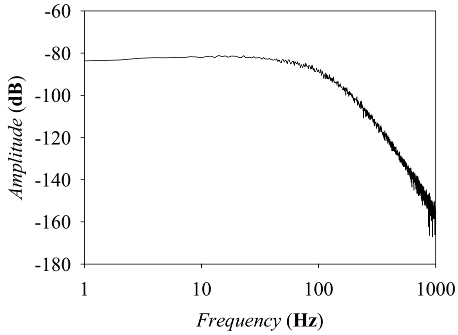

Figure 8: The output response vs. frequency diagram.

4. Conclusions

Remarkable B-V characteristics of a planar CMOS micro fluxgate magnetometer, responding to different harmonic frequencies from the fundamental to the 4th harmonic, have been successfully extracted and reported in this paper. Based on our characterised results, the fabricated fluxgate sensor is able to operate along a nearly linear B-V relationship around the zero-magnetism point if the 4th harmonic frequency is employed, or work around the non-zero point region with other harmonic frequencies if a D.C. magnetic field is compensated. An effective approach to improve the maximum responsivity of the sensor at the 4th harmonic frequency is also demonstrated. The micro fluxgate sensor is verified to feature enhanced responsivity up to 174.62 mV/T and a rapid response time of 0.01 s. These results may provide a linearly effective solution for low magnetic field detection between -0.5 mT and 0.5 mT .

5. Acknowledgements

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